CHAPTER 6

Structural Synthesis

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CHAPTER 6

Structural Synthesis

Introduction

1 The purpose of this chapter is to describe the steps that must be taken in the creation of the design of the structure of a ship, as well as the processes that may be used to ensure that the design is consistent and will meet the operational requirements and acceptance criteria. Analysis techniques will be discussed in subsequent chapters but here the means of initial synthesis and development to a viable structure will be covered.

2 The conception of a ship design does not require any detailed consideration of structure, indeed at the earliest stages the aspects of the design which are under discussion may not form a consistent or viable set and it may not even be clear what type of vessel, for example monohull of SWATH (small waterplane area twin hull), is to be the solution. As stated in Chapter 1, it is important that the designer is aware of the restrictions that the fully developed structure will place on his design in terms of space, weight, structural continuity and cost, but no more than that. Structural synthesis really commences at the end of what is defined in Chapter 1 as initial design and the bulk of this chapter will concentrate on the first iteration onwards. However, guidance is also given on ways of estimating structural weight and centre of gravity at the initial stage.

3 The term ‘designer’ is used throughout this chapter without being precisely defined. In fact, at the initial design stage the work is likely to be carried out entirely by the ‘owner’s’ designer but, as the definition of the new design emerges, the work will increasingly be carried out by the chosen shipbuilder or design consultant, with the owner keeping a watching brief. At the contract definition stage it is likely that the majority of the work will be done by the shipbuilder. This distribution of responsibility is awkward to control and the project design authority must take special care to ensure continuity and consistency of design philosophy.

4 The cost of structure cannot be covered explicitly as it is dependent on too many factors outside the strict control of the structural designer. Nevertheless, there are many things the designer can do to keep costs down and, in the main, these can be summed up by saying ‘keep it simple’. Unless very unconventional materials are to be used, the cost of structural material is a small proportion of structure cost and an even smaller proportion of the cost of a complete warship. Consequently, the way to minimise the cost of structure is to make it easy to build so as to minimise labour costs. Labour man-hours are expended mainly in the construction of small complex parts and in welding together many short lengths of plate and stiffener, especially in restricted spaces as described by Usher and Dorey (1982), as well as in repairing structure which has been damaged or distorted in the assembly process. Provided that the extra weight has been allowed for at the initial stage of design, it is clearly preferable from the point of view of

fabrication cost to make the structure relatively heavy with thicker plate and a minimum of connections and stiffeners and, in particular, avoiding complex shapes and changes of section. At the same time, if it can be managed within the constraints of the overall design, the extent of light internal structure should be kept to a minimum, as it is difficult to assemble and keep flat and will tend to take load from the main structure for which it is not designed and so will become distorted. It also reduces the size of spaces and makes access for construction more difficult and costly. As an alternative to built-in minor structure, non-loadbearing partitions which are fitted after the majority of the major structure is completed should be considered. Note that the above recommendations on weight apply only to monohull displacement vessels and not to ships such as high speed planing craft for which weight minimisation is essential.

5 A check-off list is included at the end of this chapter as an aide-memoire to the designer on the tasks required to be undertaken at each stage. However, the stages are never as clear cut as they may appear and there will always be a need to backtrack and to conduct local iterations around detailed aspects of the design. The important point is that all the tasks should be completed in a consistent manner so that the design process results in a well coordinated structure.

Initial Design

6 The initial design phase consists mainly of exploring a number of concepts in relation to the operational requirements and the results will be described in terms of overall dimensions, weight, space and rough layouts as well as some parameters such as curves of area. As suggested above, the only impact of structure at this stage is to ensure that the weight and centre of gravity estimates are reasonable and have sufficient margins to enable a satisfactory structure to be designed at a later date without invalidating the balance between weight and volume. Any layouts must also allow adequate continuity of the primary structure, and dimensions such as deck height must leave space to fit adequate stiffener scantlings. It is important also that the length to depth ratio of the hull (including effective superstructure) should not normally be allowed to increase beyond about 12.5 and should only be greater than 14 in exceptional circumstances, as it then becomes very difficult to provide efficient longitudinal structure within normal space and weight constraints. At the other end of the scale, as length to depth ratio reduces below about 8 or 9, secondary loads rather than primary loads begin to constrain the minimum scantlings.

7 The simplest and most reliable way to make estimates of structural weight is to scale from one or more type of ships for which the structural weights are accurately known. (It is not good practice to scale from another concept design which has never been completed or built, as any inaccuracies or inconsistencies will not have come to light. Estimates based on estimates are always risky.) The scaling may either be done from the overall structural weight or from the individual components such as decks and bulkheads or indeed, in the case of decks, from deck *area* to give adequate *space*. If scaling from the overall weight, care must be taken to make proper allowance for discrete numbers of components, for example as hull depth increases the number and weight of decks will only increase when an integral number of deck heights is exceeded. The same applies, although not so precisely, for a number of bulkheads in a given ship length.

TABLE 6.1
Structural Weight Scaling Factors

Structure	Weight Scale Factor	Remarks
All primary effective longitudinal structure	$L^3BT/(D\sqrt{\sigma_y})$	Alternative to the next four items
The bottom	$BL^3/(D\sqrt{\sigma_y})$ or $LB\sqrt{(T/\sigma_y)}$	Whichever is the greater
Hull sides	$LD/\sqrt{\sigma_y}$	
Upper deck	$BL^3/(D\sqrt{\sigma_y})$	
Effective superstructures	$BL^2L_s/(D\sqrt{\sigma_y})$	
Short superstructure	$(B+2d_s)L_s$	L_s is length of superstructure, d_s is height of superstructure
Internal decks	LB	
Transverse bulkheads	$BD^{3/2}/\sqrt{\sigma_y}$	

8 *Table 6.1* lists recommended weight scaling factors for conventional monohull vessels. Similar factors will be contained within commonly used concept design computer programs and, even if such a program is to be used to estimate weights, the factors in *Table 6.1* are still valuable as a guide to the designer on the influences of changing dimensions. The listed factors are derived partly from experience but mainly from simple geometric considerations, and direct geometric methods may also be used for scaling centres of gravity. It is important, however, that the structural components used as a basis for the scaling exercise are a consistent set and ideally should be from the same ship. If taken from different ships it is essential that the type of structure, for example longitudinal or transverse framing, or the use of Tee sections or bulb flats for stiffening, should be the same in all the type ships, and that the same structural acceptance standards have been used. Where it is not possible to find a single suitable type ship then the best approach is to use the smallest possible number to span the desired characteristics of the new design and to scale from each separately, comparing the results. If the results are reasonably close, say within 20% of each other, then they may be averaged; if there is a marked discrepancy between results for any component then a detailed investigation will be needed to discover why, and it will usually be found that either there is a data error or that one or more of the type ships is inappropriate for the particular application. Never ignore unexplained differences as there will always be a good reason which could strongly affect the new design. In all cases where scaling from type ship data is used, care must be taken that the type ship weight groupings are the same as that for the new design.

9 Although it is suggested above that results from different sources may be averaged, it is critical that adequate margins are allowed for subsequent design development. It is not possible to lay down firm guidelines for such margins and the designer must use common sense, however, around 10% is probably reasonable at this early stage. Some guide may be derived from the scatter in results if more than one type ship is used, and it may be better to take the worst result with a small margin rather than the average with a larger margin. However, beware the trap of taking the worst case for some components and the average for others, and so deriving yet another inconsistent set.

10 The above factors apply strictly to conventional monohull vessels. The same principles will apply to scaling from any other type of hull although there is likely to be rather less available hard data and so margins will need to be considered with some care. In addition, critical loads may be different on other types of hull, for example transverse rather than longitudinal wave loads dictate SWATH scantlings as discussed by Sikora et al (1983), and so the parameters in the scaling factors may have to be modified. In the extreme, where there are no suitable type ships, or where scaling factors cannot be deduced, it will be necessary to estimate weights from first principles; that is, to make a first shot at scantlings based on the size of the component in question and the likely loads, and to calculate the mass. In this case fairly large margins, either in scantling sizes or on the weight estimate, will be advisable. Clearly, in these cases more iterations in the design process will be needed to converge to an acceptable solution.

Synthesis at First Iteration

11 The remainder of this chapter will assume that a conventional monohull structure is to be pursued although similar techniques may be derived for other configurations. In the main, the analysis methods presented in subsequent chapters will be applicable to any configuration of structure provided that a reasonable estimate of the critical loads can be made.

12 A number of parameters will be decided at the end of the initial design of the ship, generally as preferred values within a range. These parameters will include:

Length
Beam
Draught
Displacement
Prismatic coefficient
General profile (approximate position of deckhouses, etc)
Waterline shape
Curve of areas
Number of continuous decks.

13 The object of the first structural iteration is to create a structural description and to develop it to the point where reliable estimates can be made of the weight and vertical bending stiffness of the primary structure and their distribution along the length of the ship, together with the neutral axis position and the centre of gravity. These estimates now relate directly to the ship being designed and will have diverged from the type ships originally considered. Furthermore, the description must be consistent with the layout that has been developed, particularly for deck heights, structural continuity and superstructure effectiveness, and must be such that the subsequent detailed design of the structure, which will have to meet predefined acceptance criteria, will match the description within expected tolerances.

14 The first task is to sketch a rough *structural* profile developed from the *layout* profile that will already have been defined. The purpose of the structural profile is to define all the primary longitudinal structure for subsequent estimating and design, and to ensure that adequate structural continuity is being maintained. In particular, it is necessary to ensure the continuity of the upper (strength) deck and the inner bottom, if fitted, and to make sure that superstructure blocks are ended on bulkheads or deep transverse structure. If the superstructure is to be fully effective and to contribute to primary strength then it must have *main* transverse bulkheads under both ends and at not more than 15 m intervals along its length, and these intermediate supports should extend at least one deck height into the superstructure (superstructure requirements are discussed in more detail in Chapter 8). It is also necessary that a main transverse bulkhead is sited at the after cut-up, and in these contexts a main transverse bulkhead is defined as one extending at least two deck heights from the point of load. If the positions of masts are known then these must be stepped on stiff structure extending down at least two deck heights. For more details of the requirements for continuity see paragraph 40.

15 To complement the structural profile, a sketch of the upper deck will be necessary to define the arrangement of holes for uptakes, downtakes and other significant access openings as these will affect the extent of primary structure. The holes should be arranged, as far as possible, in a block running fore and aft and with their long dimension lengthwise; small holes should be positioned so as to be in the 'shadow' area of larger holes as indicated in *Figure 6.1*. See also Chapter 12 and *Figure 12.4* for a more precise definition of shadow areas and the optimum arrangement of holes.

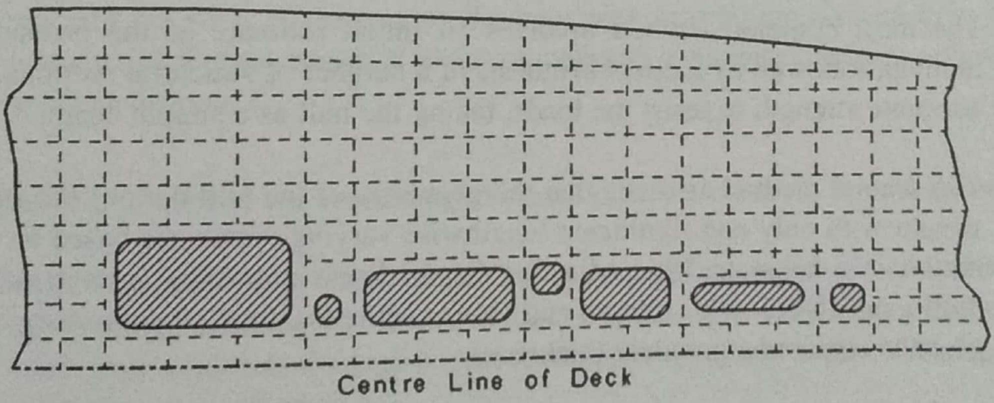

Figure 6.1 Well Arranged Holes in a Strength Deck

16 Returning to the structural profile, the question of superstructure effectiveness was raised in paragraph 14 and the philosophy of superstructures needs to be briefly discussed. It is not possible to lay down simple rules on whether a superstructure is to be regarded as structurally effective and designed as the upper flange of the hull girder, or whether it is to be regarded as ineffective and design in such a way that stresses in it and beneath it are minimised. The longitudinal extent of the superstructure, its general proportions, breadth and height compared with the depth of the main hull all bear on the question. Furthermore, the balance between structural topweight and stability will also have to be considered. These aspects are discussed in more detail in Chapter 8.

17 Because the slamming component may raise the bending moments in the forebody to the level of those amidships, as discussed in Chapter 3, it is necessary to design the structure to be as strong at about 0.15L from amidships as it is at amidships. Therefore, however efficient it may be, there is little point in treating the superstructure as a major strength member unless it extends some distance forward of 0.15L forward of amidships to some way abaft amidships. Additionally, wherever the ends of the superstructure are, they always constitute major structural discontinuities which are difficult to design efficiently and are likely to be a source of fatigue damage throughout the life of the vessel. Consequently, it is better to have the majority of the required volume within the main hull and to have the minimum of erections on the upper deck, which can then be integrated with internal supporting structure without too much disruption to layout. If, for reasons outside those concerned with structure, it is necessary to have a large volume of superstructure, then it will usually be structurally more efficient to arrange it as a single block and to use it as part of the hull girder. Many short deckhouses will provide a larger number of discontinuities, and arranging supporting bulkheads at the ends of each will be a significant constraint on the layout. The only alternative, as suggested in Chapter 5, is to use a low stiffness material such as fibre reinforced plastic, in which case the strains in the steel upper deck when passed to the superstructure only give rise to very small stresses, and the deckhouses may be considered as a first approximation to be structurally decoupled from the strength deck.

18 Having decided the general configuration of the primary structure the next stage is to estimate in some detail the weight of that structure. There are two main routes that may be followed:

a. The most common method involves an initial estimate of the primary bending moment followed by a direct synthesis of a number of structural sections to provide adequate strength to resist the loads, taking the hull as a simple beam.

b. The second method assumes that the geometry of the hull defines the strength and weight with only one significant lengthwise varying parameter based on equivalent material thickness, and then adjusting that thickness and weight in an iterative manner until a match between strength and load is achieved, finally synthesising sections to give the required equivalent thickness.

Both these approaches are described in the following paragraphs.

Estimation of Structural Weight - First Method

19 Chapter 3 presents a number of methods for prediction of vertical wave bending moment, but the majority of the procedures require a detailed knowledge, at the least, of the longitudinal mass distribution of the ship, which is not yet available at the stage so far reached in the design; even if there is adequate information on the non-structural weights, there is still no information on the *distribution* of structural weight. Consequently, the estimation of bending moment must, at this stage, be based on displacement together with any relevant parameters from the list in paragraph 12. As very much a first approximation, John's (1874) formula may be used, as described in Chapter 3, paragraph 9, but its relevance to warships is doubtful, and the margins which should be applied are far from clear. Better expressions based on bending moments derived from strains measured at sea on modern warships are as follows:

$$M_{ws} = (g\Delta L/100)\,(9.0 - 0.02L - 0.5 \times 10^{-4}L^2) \tag{6.1}$$

$$M_{wh} = (g\Delta L/100)\,(3.0 + 0.02L - 1.1 \times 10^{-4}L^2) \tag{6.2}$$

where M_{ws}, M_{wh} are the statistically expected sagging and hogging wave bending moments, L is LWL in metres, Δ is deep displacement in tonnes *including any margins and allowing for increases through life* and (gΔL) is in the same units as the bending moments. Note that both these formulae yield +ve values of bending moment and an appropriate sign convention must be applied; usually it is +ve hogging. The constants in the expressions are derived from curve fitting to plots of bending moment against length for ten ships of various sizes and should provide a generally conservative estimate.

20 Equations 6.1 and 6.2 give the statistically expected wave bending moments in a ship life as defined in Chapter 3. To obtain a design bending moment a suitable factor must be used, as discussed in paragraph 29 of Chapter 3, and then the still water bending moment must be added. The estimation of still water bending moment is no easier than for wave bending moment but, as it is usually of much lower magnitude, precision in its estimation is less critical. The simplest method is to carry out static balance using the buoyancy distribution derived from the curve of areas and a mass distribution which is based on constant volumetric density, allowing for any known concentrated masses.

21 A suitable procedure for estimating the mass distribution curve is as follows:

a. Add to the curve of areas, at sufficient sections to define the new shape, an area defined by the freeboard, beam and flare so as to estimate the area up to the upper deck and draw a fair line through it. (An assumption of a trapezoidal hull shape above the waterline is good enough.)

b. Add to the curve blocks of area to allow for the superstructure volumes.

c. Find the volume and centre of volume of the new area curve.

d. Deduct from the displacement and LCG (which should both include all margins) any known heavy masses such as towed array or minesweeping winches, gun mountings or diesel engines (lower density items such as gas turbines and all variable weights including liquids may be ignored).

e. Calculate the mean density from the volume at c. and the reduced mass at d.

f. Scale the area curve from b. by the density from e. to give a curve of mass/unit length.

g. 'Swing' the ordinates of the mass/unit length curve to give the correct *reduced* LCG from d. (a method of swinging ordinates is given by Chalmers (1982) and is a simple mathematical technique for adjusting the x coordinate of each ordinate so that the area under the mass distribution curve is maintained, but the centre of area is moved to the required position).

h. Add back the concentrated masses at the correct ordinates to provide the final predicted mass distribution curve.

j. Integrate this curve to check that the displacement and LCG are as expected.

Clearly the mass distribution derived in this way may also be used to estimate wave bending moments by balancing on a wave of appropriate height. However, the accuracy is not predictable and the use of formulae such as those in paragraph 19 is always recommended, based as they are on measurements from sea.

22 The design bending moment at amidships may now be extended to cover the full length of the ship using a standard distribution; a so-called '(1-cos)' distribution is probably as good as any, that is, in this context

$$M_x = M_o \{1 + \cos(2\pi x/L)\}/2 \qquad (6.3)$$

where M_x is the bending moment at any point x along the length (amidships zero), and M_o is the bending moment at amidships, either sagging or hogging. However, the effect of slamming extends the maximum bending moment forward of amidships as described in Chapter 3 and as indicated in *Figure 6.2* where the chain dotted line should be used for design purposes.

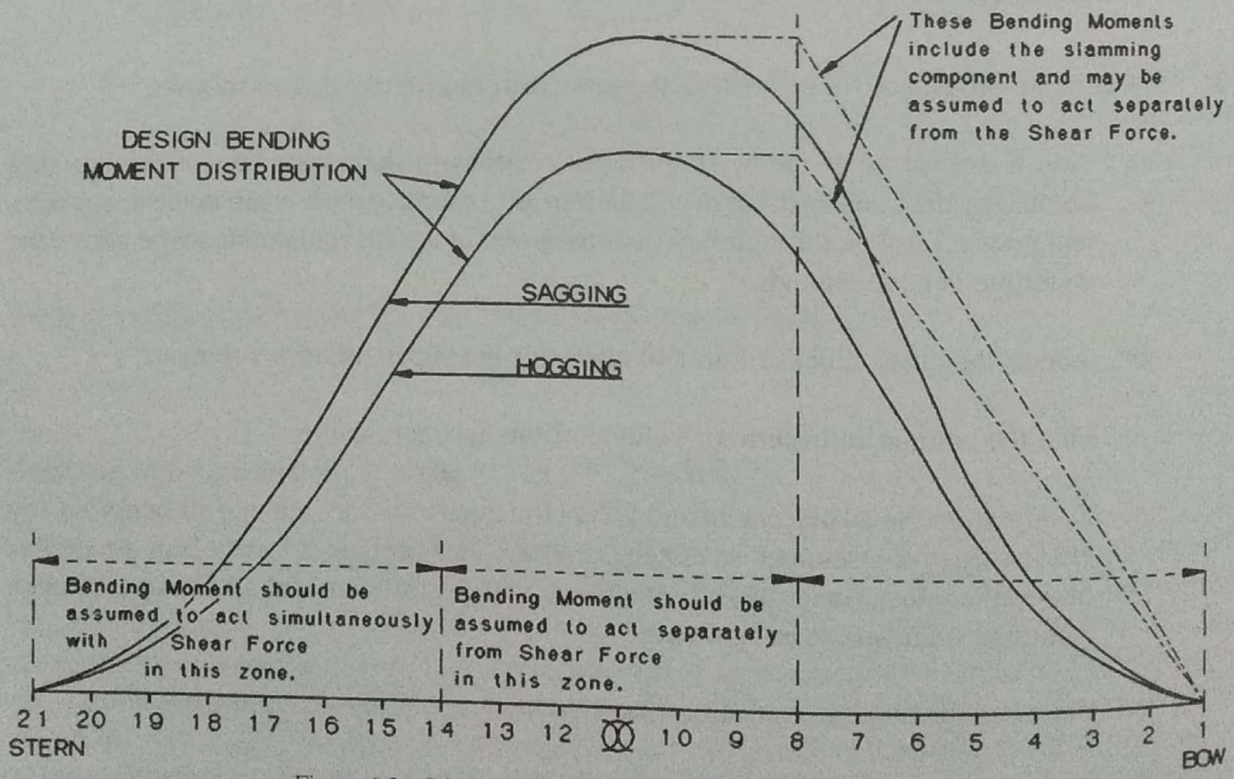

Figure 6.2 Distribution of Design Vertical Bending Moments

23 With a design bending moment available at any section along the hull it is a simple matter assuming beam theory to calculate the required section modulus if a suitable allowable stress is available. A material will have been chosen using the guidelines of Chapter 5: If the material is a ductile one such as steel, as it most likely will be, then the critical modes of failure will be a mixture of yielding and buckling, as will be described in later chapters. However, the yield strength of the material is the only relevant property of the structure which is not dependent on the detailed design and so it is necessary to base the acceptable stresses on yield alone. Nevertheless, it is possible to take some account of the style of structure if any decision has so far been made on the closeness and complexity of the stiffening (see paragraph 4), and recommended maximum *compressive* stresses (which are the limiting stresses in a conventional stiffened plate structure) as a proportion of the yield stress are given in Table 6.2; the reason that the stresses permitted in the bottom are lower than those in the deck is because of the influence of lateral pressure. Note that the stresses in the table are those arising from an extreme bending moment that has a low probability of being exceeded, such as that derived in paragraphs 19 and 20 above and paragraphs 28 and 29 in Chapter 3. If these stresses are not exceeded then design to resist buckling should be possible without too much difficulty when this aspect is investigated later during the design process. It may, however, be desirable to design to lower stresses if there are likely to be significant stress concentrations in the structure, so that an acceptable fatigue life can be achieved, as described in Chapter 13, and in this case a maximum stress *range* (maximum hogging to maximum sagging) in steel of 300 MPa is appropriate, in addition to the recommendations of *Table 6.2*.

TABLE 6.2
Maximum Longitudinal Compressive Stress at First Iteration as a Fraction of Material Yield Strength

	Strength Deck	Bottom
Closely stiffened structure $b/t < 60$	0.65	0.54
Conventional warship structure $90 > b/t > 60$	0.57	0.43
Widely stiffened structure $b/t > 90$	0.43	-

(b is stiffener spacing at right angles to the applied stress and t is the plate thickness)

24 If a non-ductile material is to be used, such as fibre reinforced plastic, then the maximum allowable *tensile* stress should be 20% of the design tensile strength of the material irrespective of stiffening arrangement, as surface cracking of the resin matrix will occur above 25-30% of the tensile strength, allowing water take-up and degradation of properties. This is a little more conservative than the proposed margin in paragraph 52 of Chapter 5 for slowly varying loads, but is appropriate for this early stage in the design.

25 Using the beam bending formula $Z = M/\sigma$, the section moduli (Z) for deck and bottom can now be found, and the next stage is to fit a structure to those moduli from which the weight per unit length can be estimated. It is possible, by making assumptions on the shape and distribution of material around the section, to derive a value of weight directly from the overall dimensions and the section moduli. However, the algebra is tedious and more importantly in a real section both the deck and bottom values of Z are not satisfied simultaneously; one is always larger than

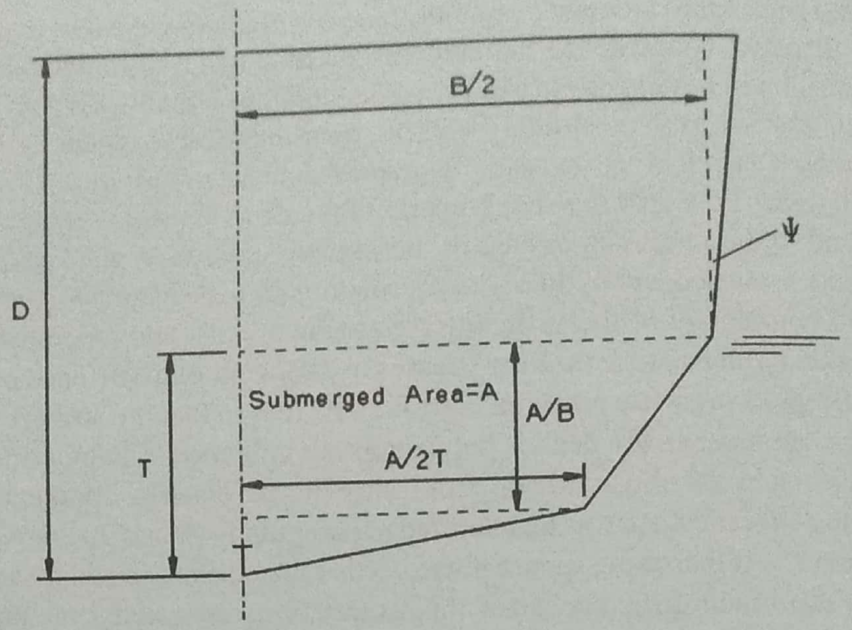

Figure 6.3 Idealised Section Shape

necessary to achieve the other. The best, if not the only, way forward is to fit a structure to the section shape by trial and error; the shape need not be the true one, indeed a simplified shape as shown in *Figure 6.3* is quite adequate, and it is not necessary to include stiffeners at this stage. An equivalent thickness of material including plate and 'smeared' stiffeners is sufficient to provide acceptable values of modulus, although clearly the thickness used must be realistic in terms of reasonable plate and stiffener size and spacing; this may mean overmatching the requirement, especially near to the ends of the ship where a minimum equivalent thickness of 8 mm is recommended, or more, say 15 mm, if the ship is to operate frequently near to the polar ice sheet (but see also Chapter 4 concerning ice operations). Remember also that the section must include any *effective* superstructure and holes in the decks when calculating the *modulus*, but all *ineffective* material or an assumed allowance for it must be included in the calculation of *weight*.

26 Enough sections are synthesised in this way to generate a plot of weight per unit length (that is, material area in a section multiplied by material density), and then the integral of this curve is the longitudinal structural weight, and its centre of area is the LCG of the same structure.

27 For material that does not contribute towards primary longitudinal strength similar, but simpler, synthesis procedures may be followed. For example, for main transverse bulkheads the load is estimated from the maximum damaged waterline that the bulkhead will have to withstand, and a simple beam calculation undertaken for a single vertical stiffener and associated plating over the maximum span between decks to establish the required scantlings and spacing. It is then assumed that these scantlings will apply over the whole of the bulkhead area, but a small enhancement may be desirable to allow for bulkhead design to resist explosive loading, as discussed in Chapter 9.

28 For minor structure it will usually still be sufficient to scale from type ship data unless there are any particularly unusual aspects of the design which need estimating from scratch. With that, enough information is available for a complete synthesis of structural weight and centre of gravity for entry to the second iteration of the design.

Estimation of Structural Weight - Second Method

29 The second method of achieving the structural weight from geometric considerations is described by Chalmers (1988(b)) and has a number of advantages over the more traditional method described above, although it has a disadvantage of requiring much more in the way of complex calculations and can only be carried out with access to the relevant computer programs. The advantages are that it is possible to obtain structural stiffnesses and effective structural weights at any section directly without the need for synthesis, relying on the fact that stiffness is strongly related to geometry but, for conventional structures, is not strongly related to distribution of material around the section. This then provides enough data on hull properties for dynamic analysis to be carried out. Estimates can be made of the response of the ship to wave and machinery excitation at a time in the design when it is possible to make changes and to avoid undesirable responses, or indeed to highlight undesirable excitations.

30 The procedure starts in the same way as before, as described in paragraphs 12-18. However, at that point the data listed in paragraph 12 is used in association with sections idealised as shown in *Figure 6.3* to calculate the second moments of area and neutral axis for a number of different equivalent material thicknesses around the girth. These material thicknesses are related to a parameter C_E, the effective structural weight coefficient, defined as the ratio of the weight of longitudinally effective structure to deep displacement, which initially is assumed constant along the length. For practical purposes C_E always lies in the range 0.08 to 0.16 and so it is not necessary to carry out too many calculations. Expressions relating beam stiffness properties to geometric parameters and to C_E are presented by Chalmers (1988(b)) and have been incorporated into a computer program which outputs data in the form of tables of second moment of area and height of neutral axis for each section along the length, for five values of C_E.

31 These computed values may be plotted against length as shown in *Figure 6.4* for second moment of area about the neutral axis (I_{zz}) which also shows the actual line of the second moment of area for a particular ship. It is now necessary to take a number of representative sections, and knowing a range of values of modulus (I_{zz}/distance of neutral axis from deck or bottom), the maximum allowable stress from *Table 6.2*, and the bending moment distribution estimated as described in paragraphs 19-21, to calculate what values of C_E are acceptable at each section, interpolating between the values of I_{zz} as necessary. At this stage, the provide adequate robustness to the structure and to leave room for refinement at later stages, it is better to keep the minimum value for C_E to about 0.1.

32 When the solutions for each section are collected together it will be seen that they comprise distributions of both moduli and stiffness (I_{zz}) along the length as well as the distribution of effective structural weight coefficient. The former may be used to carry out

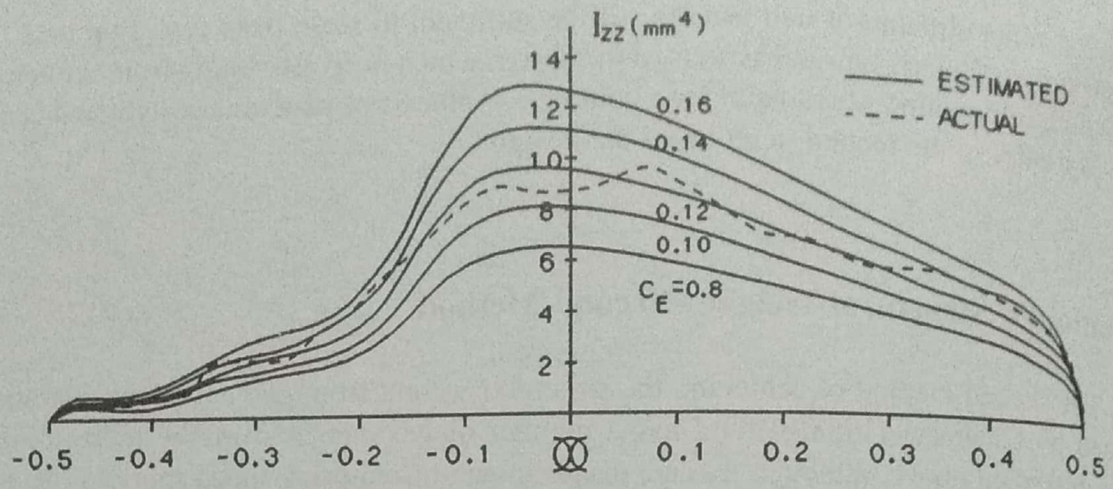

Figure 6.4 Second Moment of Area for Various Values of C_E

dynamic analysis of vertical vibration of the hull as discussed below, while the latter can be used to calculate the effective structural weight. In fact, effective structural weight is the area under the C_E curve multiplied by Δ/L and the centre of area is equivalent to the LCG of the same weight. It only remains to add in the non-effective and transverse structure as described in paragraphs 27-28 to achieve an estimate of the total structural weight as before.

33 A detailed example of how to use a dynamic analysis to check on and to adjust hull resonant frequencies is presented by Chalmers (1988(a) and (b)). It involves computing mass and stiffness influence lines for the lower vertical vibration modes and estimating from these what changes would be necessary to alter the resonances to avoid known excitations. The advantages of such an approach, which is not practicable with the first synthesis method because of the number of different sections required for a full representation of the dynamic performance of the hull, are as follows:

a. It enables conscious decisions to be made on the feasibility of changing the hull response to avoid exciting frequencies.

b. Conversely, it enables the hull designer to put pressure on equipment designers to avoid particular exciting frequencies, or to provide equipment that is not sensitive to a particular frequency, using numerical evidence.

c. With a knowledge of likely mass changes over the life of a ship the designer can be aware of how resonant frequencies are likely to change and can predict any need to take precautions against undesirable excitations long before they become necessary.

d. The effect on resonant frequencies of specific changes to the ship, either affecting mass or stiffness, can quickly be estimated.

Another useful conclusion of the reference is that mode shapes are very insensitive to realistic changes in mass and stiffness, so that once an equipment is positioned to avoid large amplitudes in any mode it is unlikely that subsequent changes or growth in the ship will compromise the original intention.

Design at the Second Iteration

34 At the end of the first iteration good estimates of the displacement and overall dimensions of the design will be available. An approximate weight distribution will have been compiled which contains a breakdown into the main weight groups (as defined in the ship specification), and the hull form, profile and upper deck layout will have been developed in some detail. The aim of the second iteration is to provide firm structural weight, space and centre of gravity budgets and, to achieve this and, indeed, to complete the structural design in a proper timescale, it is necessary to start on the detailed design of the major structural components.

35 The first task is to refine the estimation of the design vertical bending moments and shear forces. Using the mass distribution developed during the first iteration and the current hull form the full methods of Chapter 3 may now be invoked, comprising either static balance or a strip theory calculation. Whichever method is used the result should be a bending moment and shear force distribution which has a known low probability of being exceeded in the life of the ship.

36 It is next necessary to estimate the efficiency of the superstructure and to make a final decision on whether it is to be regarded as part of the primary hull girder. The procedure for this estimation is given in Chapter 8 and the outcome of the calculation is a distribution of efficiency along the length of the deckhouse. Even if the structure was originally expected to be effective, if the maximum efficiency along the length is less than 75% then it is advisable to continue the design as if the superstructure were ineffective. Whether the superstructure is effective or not, unless it is of a low modulus material, it will still take load from the deck and stress concentrations around the ends will result. The supporting arrangements to the superstructure should be reviewed to ensure that there is adequate stiff structure underneath, as required by paragraph 14 and, if necessary, or indeed possible, the number of superstructure blocks should be reduced so as to achieve either minimum above deck volume or a single, long, structurally effective block.

37 The next step is to make a first attempt at the detailed scantlings of critical sections. A procedure for assembling adequate scantlings is given in Chapter 7, but it should be noted that as the General Arrangement of the ship will still be somewhat fluid at this stage some assumptions will need to be made on the overall sizes of deck grillages, and it is best to assume grillage spans to be large and if possible between main transverse bulkheads. This allows much more flexibility in layout of minor structure, especially as later in the life of the ship when the original structural philosophy is likely to have been forgotten it may be that minor structure is rearranged to suit new equipments or layouts. This approach runs counter to the requirements for the most efficient lightweight structure where minor structure should act as panel splitters, but is a more practical solution as well as permitting the use of lightweight non-loadbearing partitions (see also paragraph 4).

38 The definition of 'critical sections' at which scantlings are required needs some explanation. The purpose is to provide structural descriptions at each section where stresses are likely to dominate the scantlings. Ideally, of course, scantlings should be defined from knowledge of the applied stresses at all points, but such an arrangement would clearly be impracticable as it would involve continuous changes in scantlings and be in direct contradiction to the policy of simple, cheap structure. Scantlings should therefore be kept reasonably constant along the mid half length of the hull allowing the properties to change due to changes in beam and draught only, while in the end quarters scantlings will be reduced in fairly large steps consistent with the applied loads. However, scantlings should not be reduced too rapidly at any one section and, for example, stiffener sizes are best not changed at the same section that plate thickness is reduced. There will then be sections along the length where there are step changes in the section modulus, and it is the weaker sides of these changes that are defined as critical sections. Note that these critical sections will also include points just outside large superstructure blocks and across large holes or sets of holes. Although there will not necessarily be a critical section at amidships, it is usual to take one at or near that section because the design bending moment is at a maximum.

39 Having created the scantlings at the critical sections and carried out simple checks on the local as well as the overall strength as described in Chapter 7, the weight of each section should be calculated and, from a knowledge of depth and beam and where it is intended to step down the scantlings towards the ends, a plot of weight per unit length can be prepared. This plot should be compared with that derived from other criteria at the previous iteration. It is likely that it will be a little lower than the earlier estimate if proper margins were used; if there is any significant divergence then the reason should be investigated and explained before any further progress is made. When the new distribution of weight is accepted it can again be integrated to give structural weight and LCG, but a margin is still necessary, of the order of 5%, to allow for detailed additions as the design develops.

40 During this stage of the design the General Arrangement of the ship will be developed in some detail, to the extent that little significant change will be possible at a later date, so the structural designer must keep a close eye on progress and ensure that structural continuity is not sacrificed to ease of layout. In particular the following requirements must be satisfied:

a. The upper deck should ideally extend from stem to stern without a step. If a break of forecastle is inevitable it must be as far abaft amidships as possible and must be supported by a main transverse bulkhead. Further information on the design of the break of forecastle are given in Chapter 12.

b. The inner bottom of a double bottom structure must be continuous over its whole length even if that involves sloping portions and some loss of fuel capacity.

c. Major longitudinal bulkheads must also be continuous over their length. If they are not straight then any changes in direction must be located at major transverse bulkheads.

d. The end bulkheads of *all* superstructure blocks (whether considered structurally effective or not) must be located over deep stiff transverse structure and it is unlikely that the structure will be stiff enough if it does not extend down by at least one deck height. The ends of structurally effective blocks must be supported by main transverse bulkheads extending downwards a distance more than 50% of the width of the deckhouse and of the full width of the hull. (In the case of a structurally effective sided or narrow deckhouse such as an aircraft carrier island, the supporting bulkheads must extend away from the deckhouse to the nearest main longitudinal structure.)

e. The sides of all deckhouses must be supported on deep longitudinal structure; if the superstructure is structurally effective then the longitudinal structure should desirably be a bulkhead of at least one deck height, and penetrations should *not* be cut in these bulkheads within a distance from the superstructure ends equivalent to three deck heights.

f. There must be an adequate number of transverse bulkheads supporting long superstructures, generally not more than 15 m apart and extending at least one deck height into the superstructure. The number of supporting bulkheads affects superstructure efficiency as indicated in Chapter 8.

g. A main transverse bulkhead must be sited at the after cut-up extending upwards by at least half the waterline beam at that section.

h. Machinery uptakes and downtakes, equipment removal routes, hatches and all other openings must be arranged in such a way that the longitudinal strength of the hull is least affected. Usually this means concentrating openings on the centreline of the ship, which then makes side passageways undesirable because of the tendency for hatches to be sited abreast of larger holes rather than between them. Another reason for avoiding holes near the ship's side is that the deck stringer strakes are relatively highly stressed compared with centreline strakes.

j. Wherever possible, weapons, sensors, masts and other concentrated loads must be sited over main bulkheads to provide adequate stiffness. For larger items such as heavy gun mountings or box section masts, a single bulkhead support may not be sufficient and a cruciform, ring or U shaped support is likely to be needed to prevent rocking motions.

k. Note that while rules for continuity of structure will be different for SWATHs and other novel vessels, similar principles to the above should still be followed.

41 The location of minor structure can be arranged to provide support for heavy items, but if it is so used it is essential that load paths are worked out and that all the gravitational and inertial loads, especially those due to explosive loading (see Chapter 15), are carried through to stiff structure. For example, pillars, which are only used for this purpose, must end either on a major bulkhead or on stiff bottom structure. Where minor bulkheads are used, the load can be diffused in shear (see Chapters 9 and 10) provided that there is adequate stiffening to carry the load to surrounding structure without causing buckling. Except as discussed in paragraph 37, minor bulkheads may also be used to break up large deck spans and to allow a reduction of deck scantlings; in such cases it is obviously essential that the minor bulkhead is never subsequently moved or otherwise altered during the ship's life, and is stiff enough to take secondary loads without suffering local buckling or cracking. The loss of a 'panel splitter' has a drastic effect on panel buckling strength as indicated in Chapter 7.

42 When this first assessment of the detailed design of structural sections is complete, and the requirements for minor bulkheads and pillars have been settled, it will be necessary to reassess the space required for the structure and to ensure that all compartments are now large enough, allowing for all expected lagging or lining. If there appears to be insufficient space then it is essential that part or all of the ship is enlarged; it is *very unwise* to ignore such warnings and to hope that it will be possible to work the structure in at a later stage. Indeed, this iteration is the last time when significant changes to the design dimensions are likely to be feasible.

43 The final activity in the second iteration, before the detailed assessment of structural weights and centres of gravity is undertaken, is to identify any special, complex or unusual features of the design which will require analysis by finite elements or model experiments. If such work is not put in hand at this stage there will be insufficient time to complete it for the results to be useful. Features that may require special analysis include large openings in primary structure, discontinuities such as ends of deckhouses or a break of forecastle, structure in way of large concentrated loads and structure where stiffness or vibratory response may be critical. It is advisable to discuss these features with specialists in stress analysis to establish the best way forward, and to obtain a realistic estimate of the structural weights and spaces likely to be required.

Design at the Third Iteration

44 At the end of the second iteration phase a reliable estimate of the displacement and the weight distribution for the new design will be available. The overall dimensions and the hull form will have been finalised within small margins and a broad General Arrangement will have been agreed. Weight and space budgets will have been considered in detail and specified within close tolerances. The third, and usually the final, iteration of the design phase is therefore a period of further refinement and improved definition. In particular, the structural work will consist, for the most part, of detailed analyses of scantlings chosen at the previous stage, followed by revision of those scantlings as necessary. On completion of the third iteration the scantlings of all major structural assemblies must be finalised; the tasks required to complete this are described in the following paragraphs.

45 The analyses of unusual or complex features, such as those listed in paragraph 43, must be progressed as rapidly as possible. As these tasks will frequently be undertaken by consultants under contract it is essential that a firm programme for completion is agreed that matches the overall ship programme and the contractors' resources, so that the design will not be delayed, or that the designer will not have to make judgements ahead of the solution being available.

46 The design bending moment and shear force distributions must be recalculated using the latest hull form and weight distribution. The method to be used should be chosen from Chapter 3, but again it is important that load factors included are well defined so that safety margins used in the structural analysis are properly matched and significant over or under design is avoided.

47 The next task is the detailed analysis of the strength of the main hull girder. This will take a significant time and should be started as soon as good estimates of design loads are available. The design must include not only longitudinal strength under both bending and shear, but also strength under transverse loading and local loading. The detailed procedures to be followed are described in Chapters 7, 8 and 9, and in later chapters for minor structure and details. On completion of the analysis, where it has been necessary to change scantlings, the weight and space required must be reassessed to ensure that the overall design criteria are still being met and that weights and centres of gravity are within budget, in other words, to check that the margins included at the previous stage were adequate. Where scantlings have been revised *downwards* it may be possible to make better use of the space and local rearrangements of layout should be considered.

48 Once the stress levels in superstructures or deckhouses have been established, allowing for the best estimate of structural efficiency as discussed in Chapter 8, their scantlings must be reviewed and revised as necessary. Particular attention must be paid to the end bulkheads of all superstructure blocks to ensure that they are strong enough to bear the high vertical loads generated by longitudinal bending of the hull. These bulkheads must be at least as thick and stiff in shear as the deckhouse sides from which the loads are transmitted and, as the loads are then passed as a direct stress to the transverse bulkhead beneath, this lower boundary needs to be effective and both plate and stiffeners need to be well aligned. (Quality control during construction is also a consideration in this area and every effort should be made to ensure that the completed structure is not misaligned by more than half the plate thickness in any direction and that welds are to a high standard.) Revision of the scantlings of the superstructure will have a bearing on the loads in the upper deck and vice versa, and therefore development of these two assemblies must be progressed together. As before, care must be taken to ensure that budget weights and centres of gravity are not exceeded or, if they have to be, then that adequate compensation is found elsewhere.

49 It is next necessary to complete the design of the main transverse bulkheads as described in Chapter 9. When designing bulkheads situated under the ends of deckhouses the high vertical loads due to longitudinal bending must be taken into account, and the structure properly integrated as discussed in paragraph 48.

50 At the end of the third iteration it should be the aim to have completed the analysis of all major structure, including any special features being analysed by contractors, so that the overall form of the structure can be defined. Subsequent analysis will only provide detail of minor structure and explore the effects of small changes to the main structure with a view to optimising it for production. In other words, the majority of the structural design work must be complete so that the remaining time can be spent in providing an adequate contract definition.

Contract Definition

51 During contract definition the aim is to provide adequate detail of the ship, including the structure, to enable an order to be placed with a shipbuilder. For the structure this involves detailed design of those assemblies and areas of the ship which have not so far been covered, and the preparation of guidance drawings and specifications. Whichever authority has undertaken earlier work on the design, this stage will be certain to involve the shipbuilder in the agreement and probably the preparation of working documents. Specific structural items that are likely to be covered at this stage are described in the following paragraphs.

52 Weights and spaces for main machinery seats will usually only have been estimated so far. With full definition of the machinery arrangement and positions it will be necessary to undertaken the detailed design of as many machinery seats as can be defined. Seating design is discussed in Chapter 12.

53 Structure subject to loads from equipment which has not until this stage been fully defined will need to be reviewed. Examples of this may be flight decks, when the detailed aircraft landing, handling and parking arrangements are known, and decks in way of missile efflux and gun blast pressures when the precise positioning of mountings has been decided. In these and other areas, adequate margins will need to have been left in the weight and space budgets for local stiffening as final details are developed.

54 Miscellaneous structures, including the following, will need to be designed:

a. Masts.

b. Shaft brackets and supporting structure.

c. Rudders.

d. Stabiliser fins.

e. Weapon supports.

Procedures for design of these and other secondary structures are given in Chapter 12.

55 Any outstanding work on the analysis of special or complex features must be completed during this phase, as they are likely to be costly to construct and it is important that they are properly defined for estimating purposes.

56 The definition of any minor bulkheads that have not so far been designed must be completed. Such bulkheads will inevitably be non-loadbearing by this stage and so may be stiffened by swedging or by simple flat bar stiffeners, but care should be taken to ensure that the effect of shock loading on small components is catered for. Generally, the shipbuilder may be left to define structure that suits his production methods, and there is little need for the structural designer to be involved. A point to be remembered, however, it that if minor structure is rigidly connected to major structure it will tend to take load for which it is not intended, and buckling or cracking in service may result, especially if it is in an area of high strain and may be a continuous drain on maintenance resources. It is better to avoid hard connections by leaving gaps if these do not compromise fire or smoke barriers, or otherwise using low stiffness materials or proprietary partitioning. Aluminium bulkheads are not recommended due to their poor fire and fatigue resistance.

57 Finally, it is at this stage that the structural guidance drawings will be being prepared which will include many standard features such as beam/frame connections and berth butt details. While these are not the direct concern of the structural designer, it is in his interest to keep a watching brief over such drawings to ensure that none of the details run counter to the design philosophy or intention. An example might be the assumption during transverse strength calculations of rigid beam frame connections, while the shipbuilder is expecting to use only part welded lapped brackets. Some further guidance on these details is given in Chapters 12 and 13.

Structural Design Check-off List

58 As a conclusion to this chapter there follows a check-off list of the activities detailed in the foregoing text to assist the structural designer in ensuring that no task has been neglected. note that this list is only directly applicable to conventional monohull vessels.

59 Initial Design

a. Estimate structural weights and space requirements.

b. Make proper allowance for structural continuity.

60 First Iteration

a. Prepare rough structural profile and upper deck arrangement ensuring continuity of major structure is maintained, especially support to the superstructure.

b. Estimate design bending moments and distributions.

c. Estimate overall ship weight and weight distribution.

d. Make initial decision on style of stiffening and deduce the equivalent maximum allowable stresses.

e. Make initial decision on effectiveness of superstructure.

f. Estimate the weight of structure needed to satisfy the allowable stresses.

g. If required, estimate hull resonant frequencies and take any necessary action to avoid conflicts with exciting frequencies.

h. Estimate the position of the centre of gravity of the structure.

61 Second Iteration

a. Calculate design bending moment and shear force distributions.

b. Calculate superstructure efficiency and make final decision on whether it is to be considered structurally effective.

c. Decide positions of critical sections.

d. Design main longitudinal structure at critical sections.

e. Design superstructure if it is effective primary structure.

f. Check structural continuity.

g. Design main transverse bulkheads.

h. Calculate structural weights and centres of gravity.

j. Define structural features that will require special analysis.

62 Third Iteration

a. Recalculate design bending moments and shear forces.

b. Start design of complex or unusual features.

c. Analyse hull and superstructure strength.

d. Design and analyse all significant structure not so far covered, including non-effective superstructure.

e. Recalculate structural weights and centres of gravity.

63 Contract Design

a. Complete design and analysis of complex or unusual features.

b. Design machinery seats and miscellaneous structures.

c. Check designs of all minor structures and structural details.

d. Make final calculations of structural weights and centres of gravity.

e. Make final checks on structural continuity and load paths.